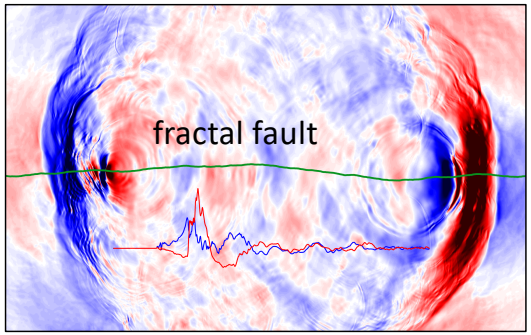
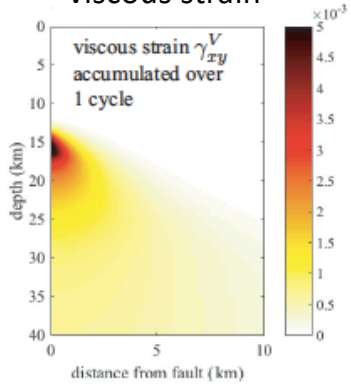
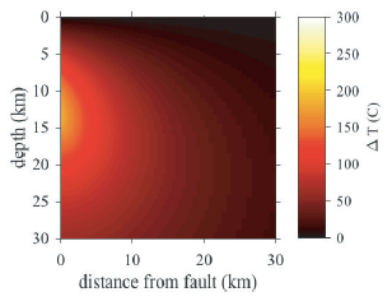
Future Directions for Earthquake Modeling: Shear Zones, Roughness, Fluid Migration, and Inelasticity

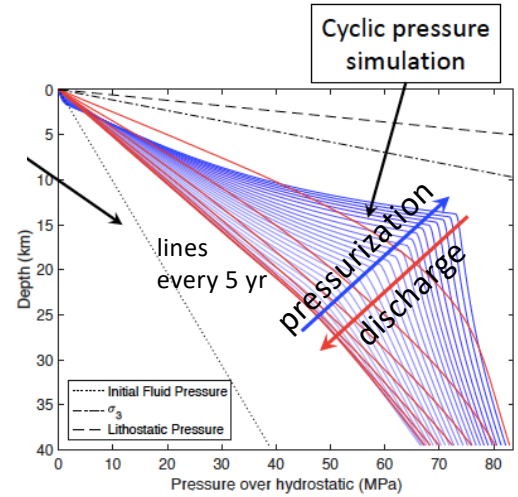


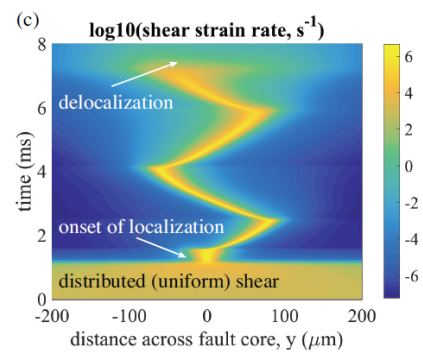
viscous strain



thermal anomaly







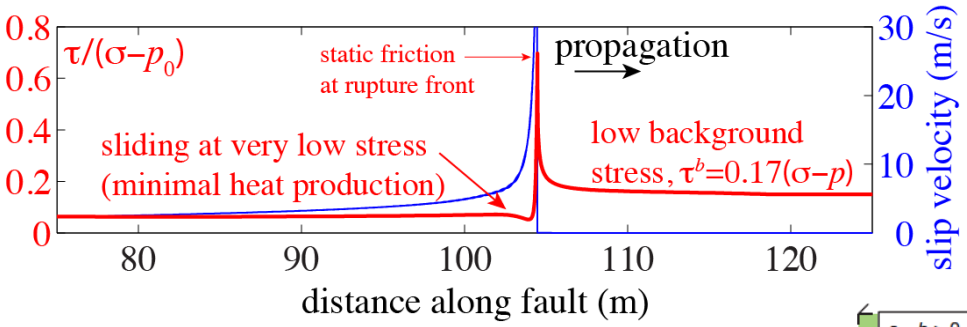
Eric M. Dunham, Stanford University

Kali Allison, Weiqiang Zhu, Elias Heimisson, Martin Almquist, Sam Bydlon, Brittany Erickson, Jeremy Kozdon, and many others

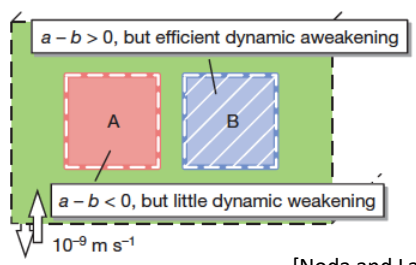
Dynamic weakening has revolutionized our understanding of fault strength evolution and rupture dynamics

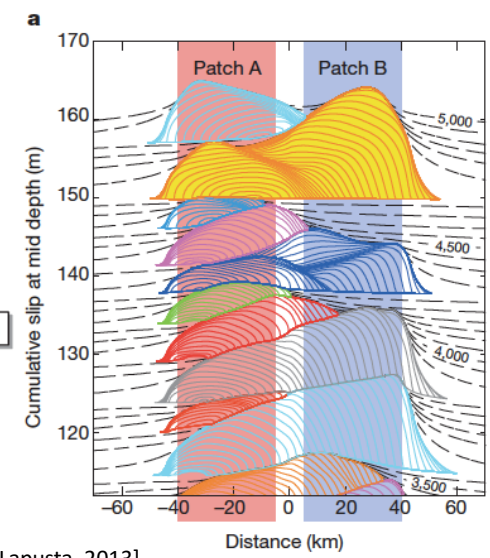
Dynamic weakening = extreme coseismic strength reduction from thermal pressurization and other effects

- permits self-sustaining rupture propagation at low background stresses (ubiquitous in experiments, consistent with stress orientation around SAF, lithospheric strength to match topography)
- minimal heat production during sliding (consistent with drilling measurements, scarcity of melt)
- important (and frightening) predictions, such as possibility of rupture through creeping fault sections



example above has thermal pressurization [Schmitt et al., 2015] but similar ideas in Lapusta and Rice [2003], Noda et al. [2009], and many other studies



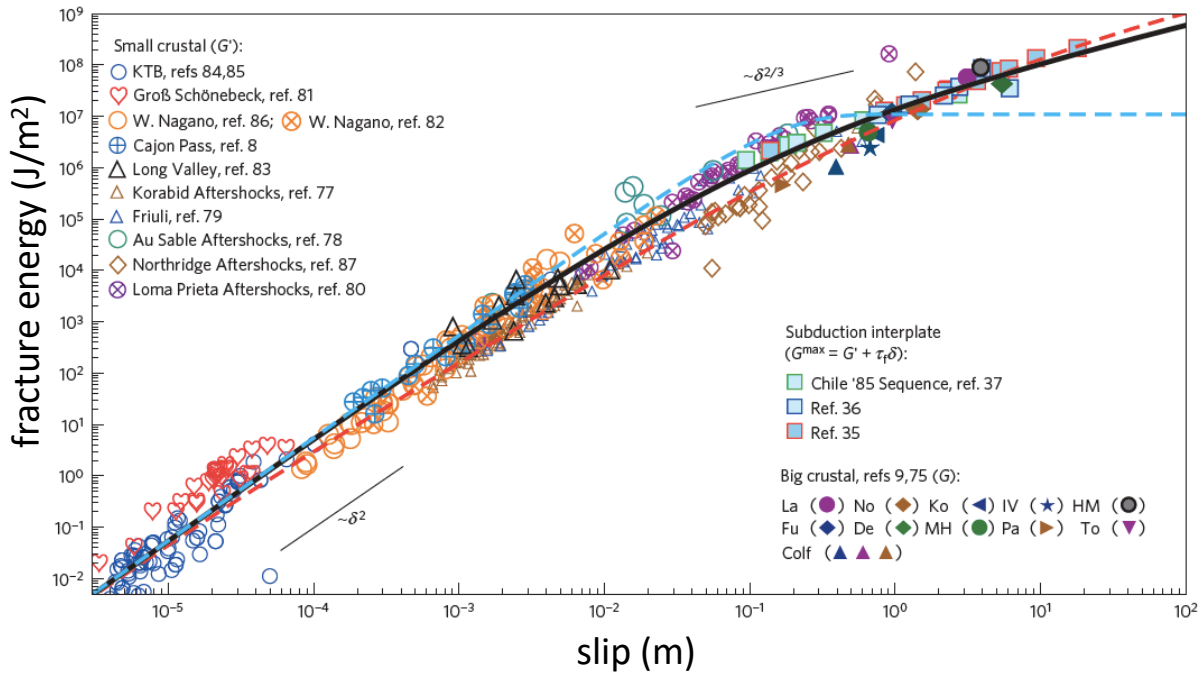


[Noda and Lapusta, 2013]

Dynamic weakening has revolutionized our understanding of fault strength evolution and rupture dynamics

Dynamic weakening = extreme coseismic strength reduction from thermal pressurization and other effects

Best validated by consistencies with heat flow and stress, as well as ***scaling of fracture energy with event size*** (not through comparison to near-source seismograms, which can be matched with any friction law having reasonable fracture energy for that event size).

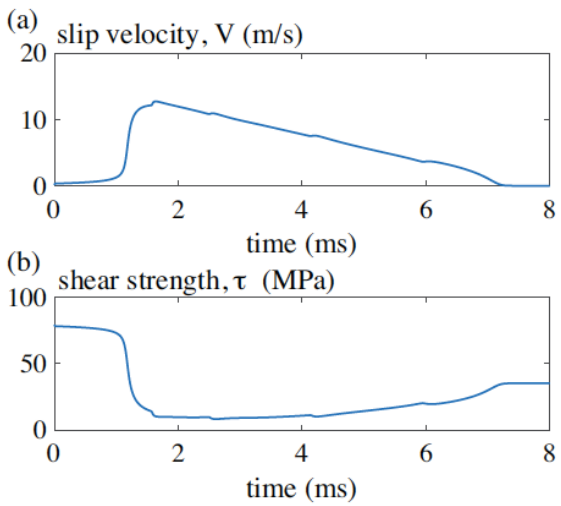


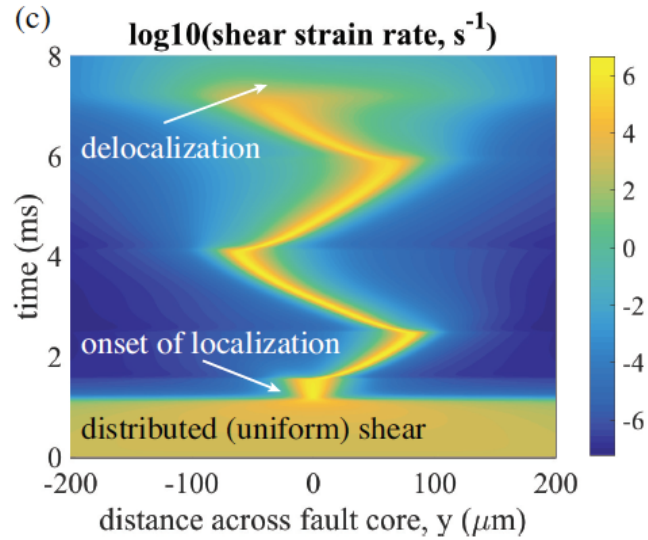
Incidentally, another possibility for fracture energy scaling—***plasticity***–has not been rigorously explored! Requires multiscale rupture simulation capabilities (adaptive mesh refinement).

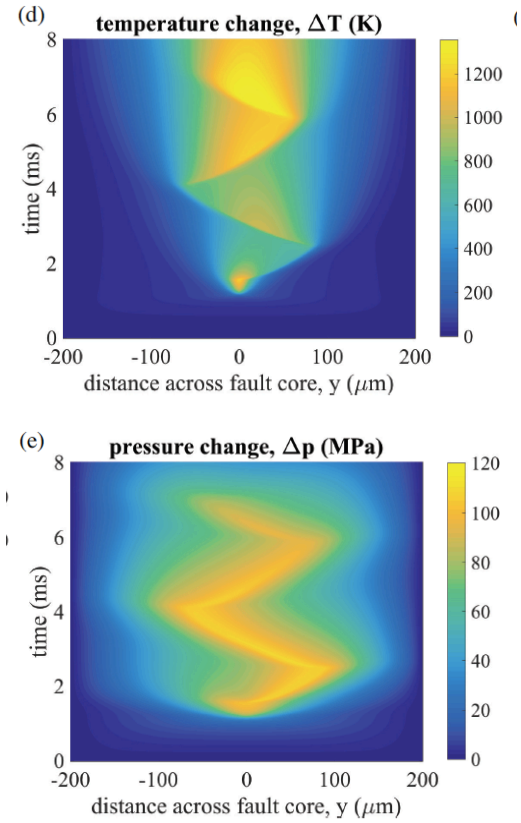
[Viesca and Garagash, 2015]

Localization (and delocalization!) is key to determining importance of dynamic weakening, especially at depth

Uniform shear of rate-strengthening gouge **is unstable** due to weakening from thermal pressurization [e.g., Rice et al., 2015; Platt et al., 2015], with shear zone width controlled by balance of pressurization and stabilizing processes like diffusion and dilatancy.





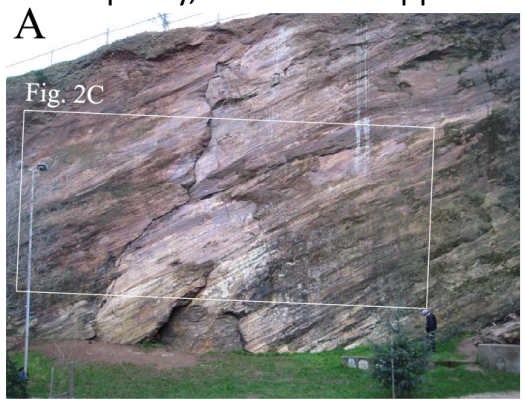


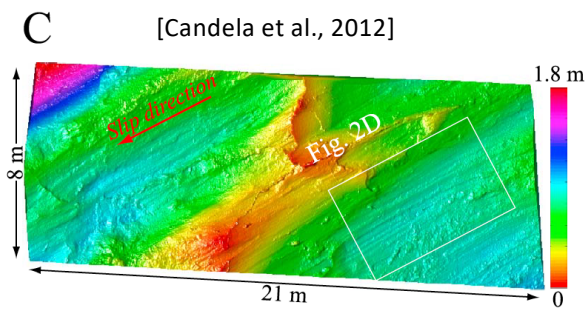
Above simulation couples shear zone model to spring-slider. Next step is to introduce to dynamic rupture or earthquake sequence code.

—but how do properties vary with depth?

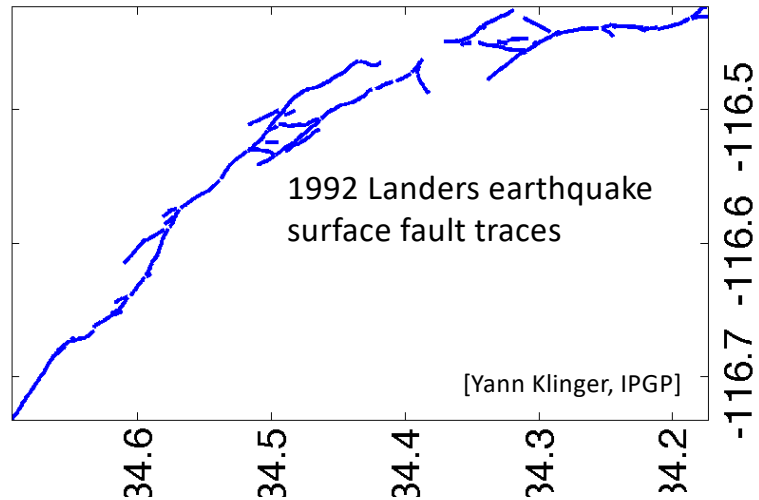
We now also recognize essential role that fault geometric complexities play in fault strength and rupture dynamics

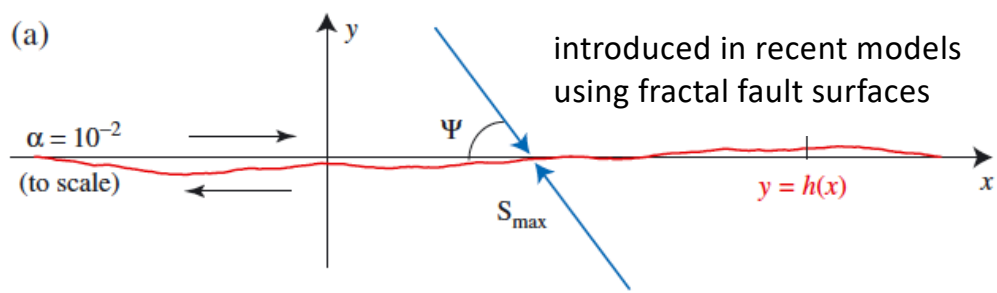
Corona Heights fault, San Francisco
(former quarry, front face stripped away)





[Candela et al., 2012]

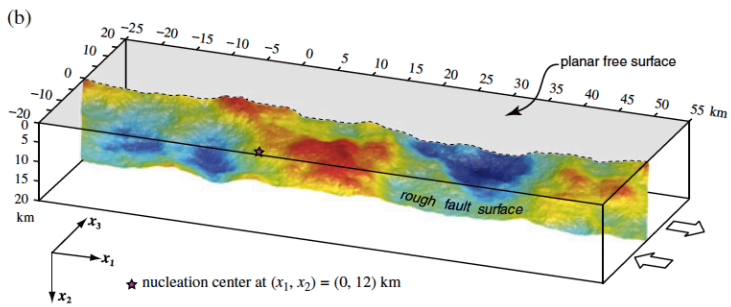




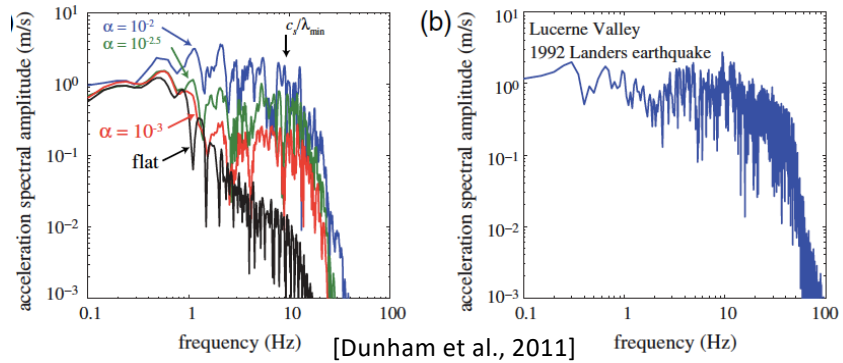
introduced in recent models
using fractal fault surfaces

[e.g., Dieterich and Smith, 2009; Dunham et al., 2011; Shi and Day, 2013; Tal et al. 2018]

Complex rupture propagation on rough faults generates realistic incoherent high-frequency ground motion



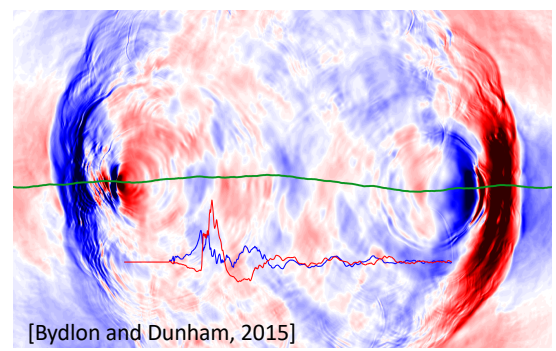
[Shi and Day, 2013]



[Dunham et al., 2011]

3D simulations by Shi and Day [2013] "…model seismic wave excitation up to ~10 Hz…, permitting comparisons with empirical studies of ground-motion intensity measures of engineering interest. **Characteristics of… synthetic response spectra… are comparable to… empirical estimates**…."

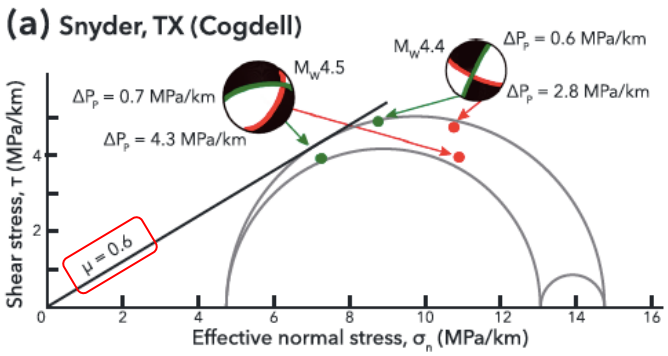
But ***unraveling source complexity from scattering*** remains unsolved. Simulations capturing both, along with off-fault plasticity, are required [e.g., Roten et al., 2016].
→ Future direction is to use ***dynamic source models*** (instead of reciprocity-based kinematic models like in CyberShake [e.g., Graves et al., 2011])—requiring extensive HPC efforts, code development/optimization, and workflows for generating ensemble realizations of stochastic simulation components

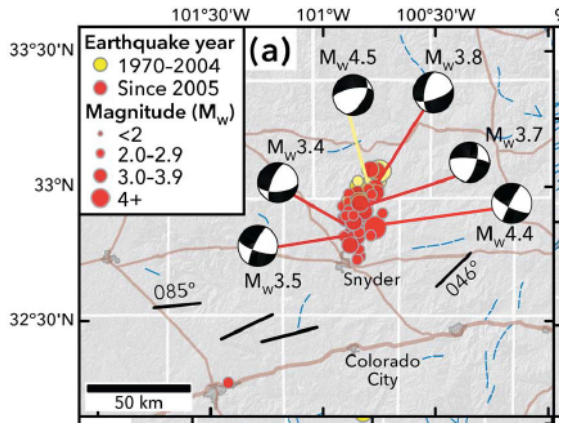


[Bydlon and Dunham, 2015]

Additional resistance from straining around structural complexities might also explain why most faults require $\tau \approx 0.6(\sigma - p)$ for rupture

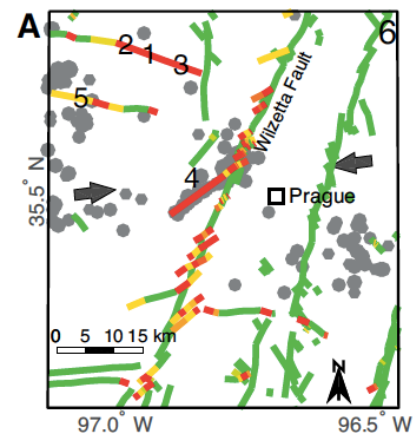
Evidence for these stress levels comes from orientations of active faults (induced seismicity), stress measurements from drilling in plate interiors





[Lund Snee and Zoback, 2016]

traffic-light color-coding based on proximity to $\tau \approx 0.6(\sigma - p)$



[Walsh and Zoback, 2016]

Additional resistance from straining around structural complexities might also explain why most faults require $\tau \approx 0.6(\sigma - p)$ for rupture

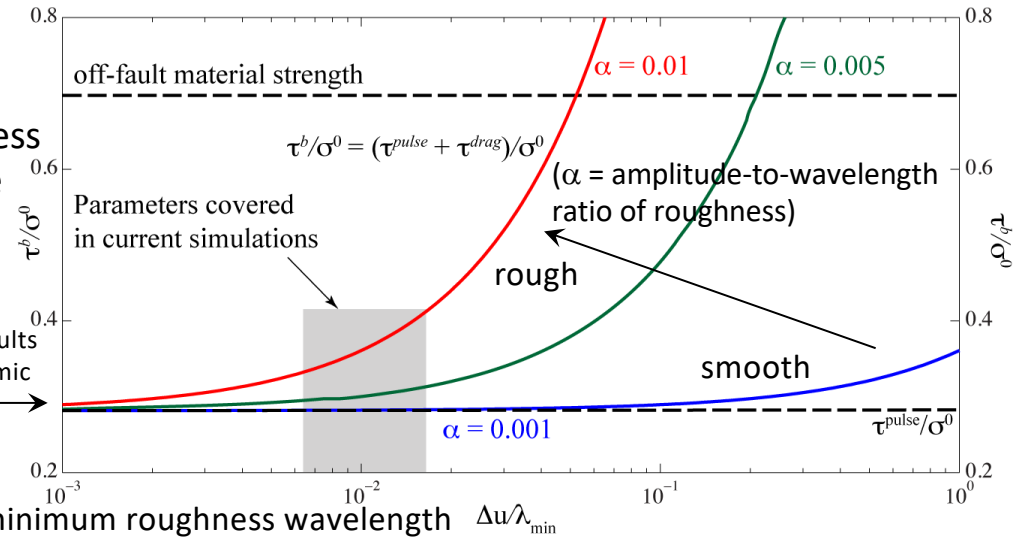
Two possible explanations for these stress levels:

1. ***dynamic weakening is unique to mature faults*** having well-developed cores prone to shear localization, heating, and thermal weakening

2. dynamic weakening eliminates frictional resistance, but ***backstress or roughness drag from geometric complexities provides additional resistance to slip***

threshold background stress for self-sustaining rupture

threshold for flat faults with extreme dynamic weakening



slip / minimum roughness wavelength

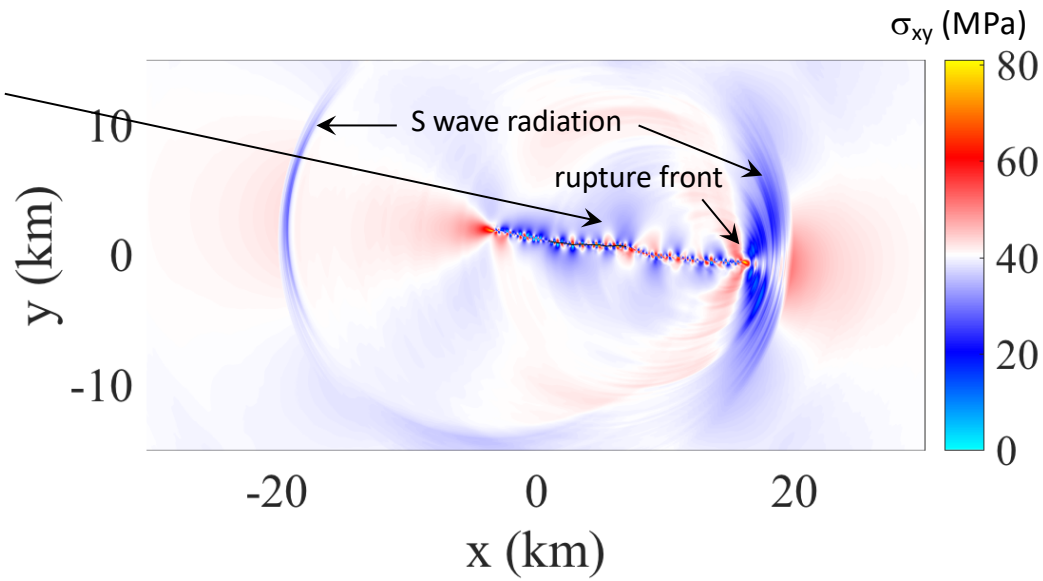
[Fang and Dunham, 2013]

Hypothesis remains untested for sufficiently short roughness wavelengths and in 3D due to computational limitations.

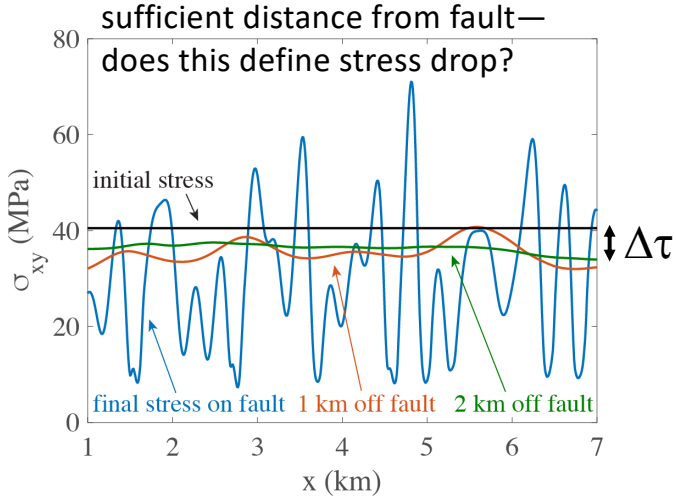
Other fundamentals—like stress drop (and relation to seismically or geodetically inferred stress drop) and overall energy balance—also remain poorly understood…

To explain issues, examine stresses surrounding rupture on fractal fault (with dynamic weakening):

highly heterogeneous near-fault stresses help explain diversity of aftershock focal mechanisms [Smith and Dieterich, 2010] and seismicity locations relative to major fault traces [Powers and Jordan, 2010]



shear stress becomes uniform at sufficient distance from fault—does this define stress drop?

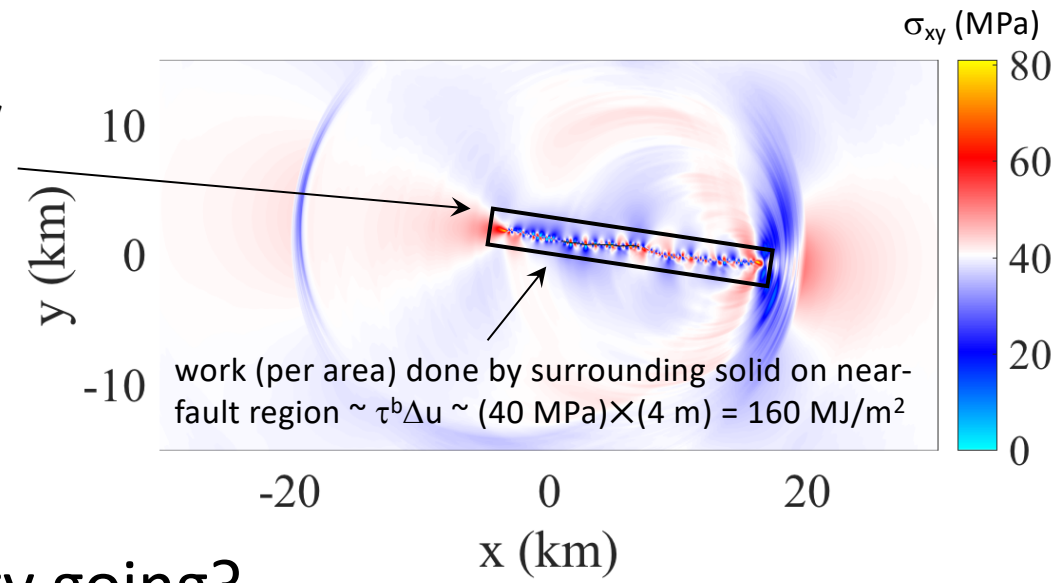


Other fundamentals—like stress drop (and relation to seismically or geodetically inferred stress drop) and overall energy balance—also remain poorly understood…

To explain issues, examine stresses surrounding rupture on fractal fault (with dynamic weakening):

Do usual **earthquake energy balance**, but expand "fault" to include near-fault region

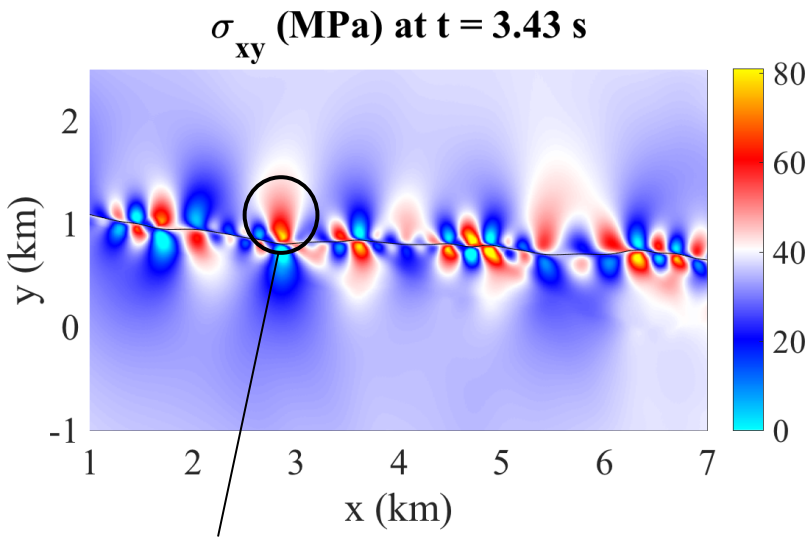
If background stress is high (i.e., $\tau \approx 0.6(\sigma - p)$), then energy flow into near-fault region is also large.



Where is the energy going?

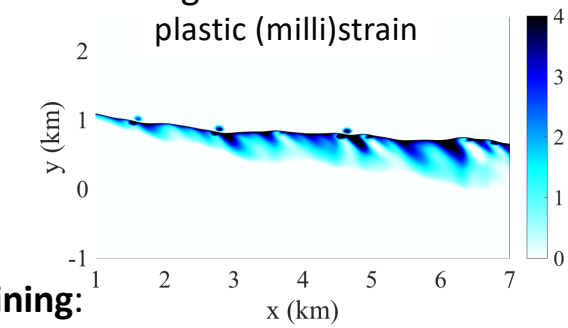
and, if it is converted to heat, how do we avoid pervasive melting and thermal anomalies around faults?

Where does this energy go?



…but these stresses trigger earthquakes (aftershocks and background seismicity) on secondary faults, which are themselves fractal surfaces, repeating this process at ever smaller scales – with each time some ***energy lost in seismic radiation***

frictional heat on fault:
can be made *arbitrarily small* with more extreme dynamic weakening



heat from plastic straining:
~1 MJ/m^2 when integrated over off-fault dimension, consistent with seismically inferred fracture energy for event of this size and not violating heat flow constraints (also, distributed so local ΔT very small)

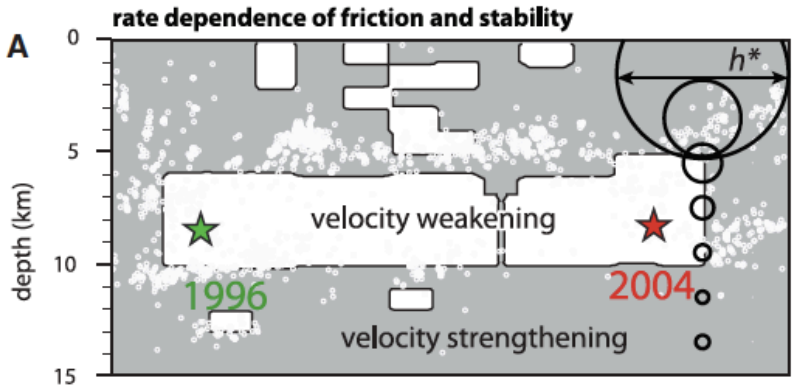
strain energy in near-fault stress concentrations:
considerable fraction of total in this simulation; even larger if roughness at shorter scales included

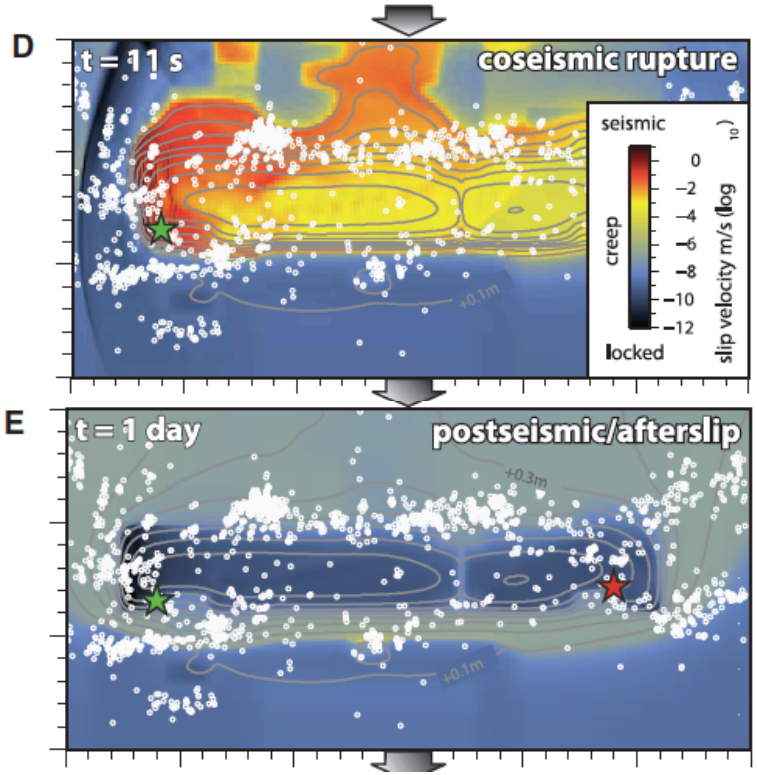
Needed: 3D simulations resolving short wavelength roughness and secondary faults, with dynamic weakening and plasticity and inertial dynamics, run over multiple cycles to quantify energy flow, radiation efficiency, etc.

Single-event dynamic rupture simulations → Sequences of earthquakes and aseismic slip (SEAS)

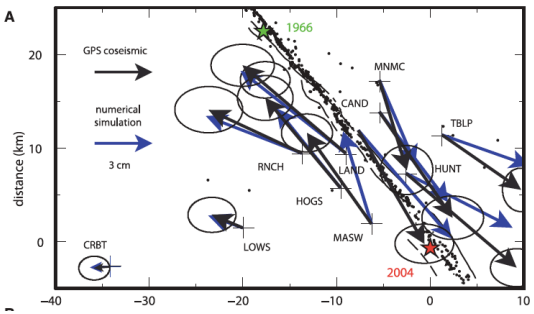
Most unsolved, forefront problems require simulation of ***multiple event sequences*** resolving coseismic slip (rupture dynamics), tectonic loading, aseismic slip (e.g., nucleation, postseismic slip, slow slip events) with realistic physics (inertia, dynamic weakening, off-fault plasticity, viscoelasticity, fluid migration and pressure diffusion)

SEAS (cycle) simulations provide internal self-consistency (between loading, initial stresses for coseismic rupture, assumed rheology, etc.) and ability to connect with multiple data sets



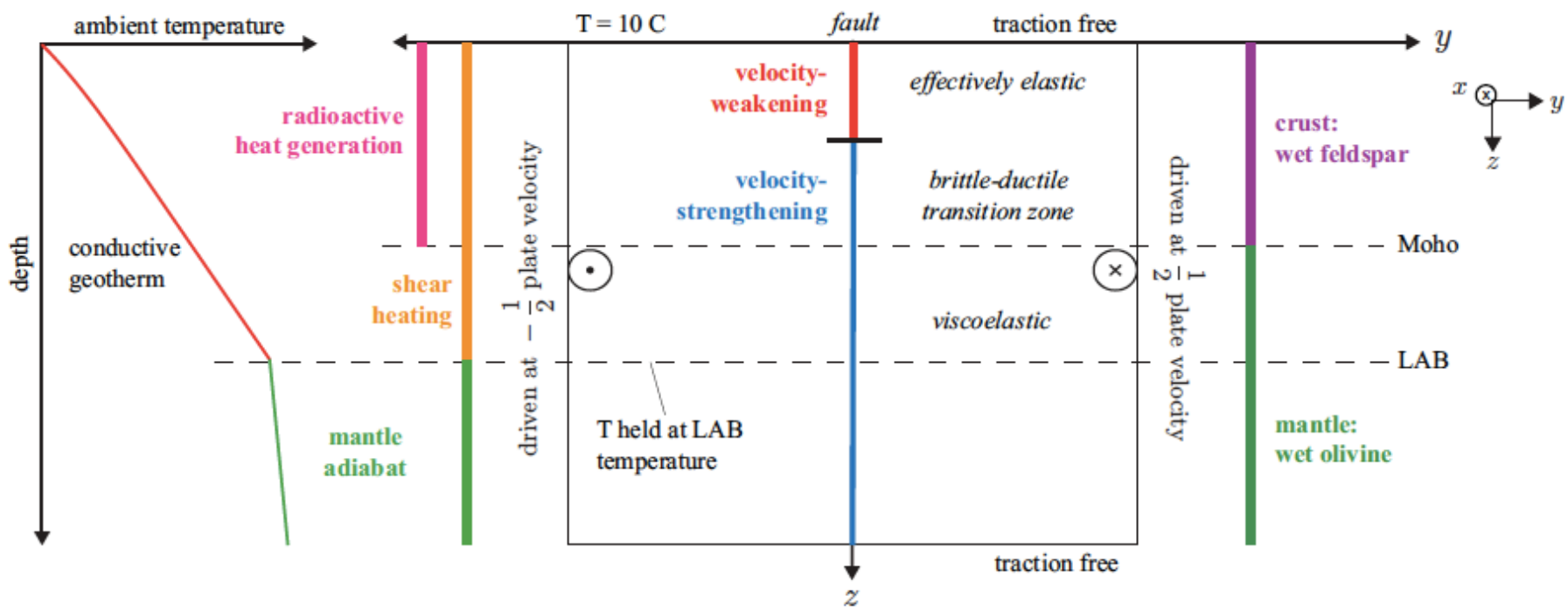


Example: Barbot et al. [2012] rate-and-state model of Parkfield earthquake sequences and postseismic response



Natural extension is to investigate more realistic viscoelastic rheology at depth

2D Antiplane Shear Strike-Slip Fault Model



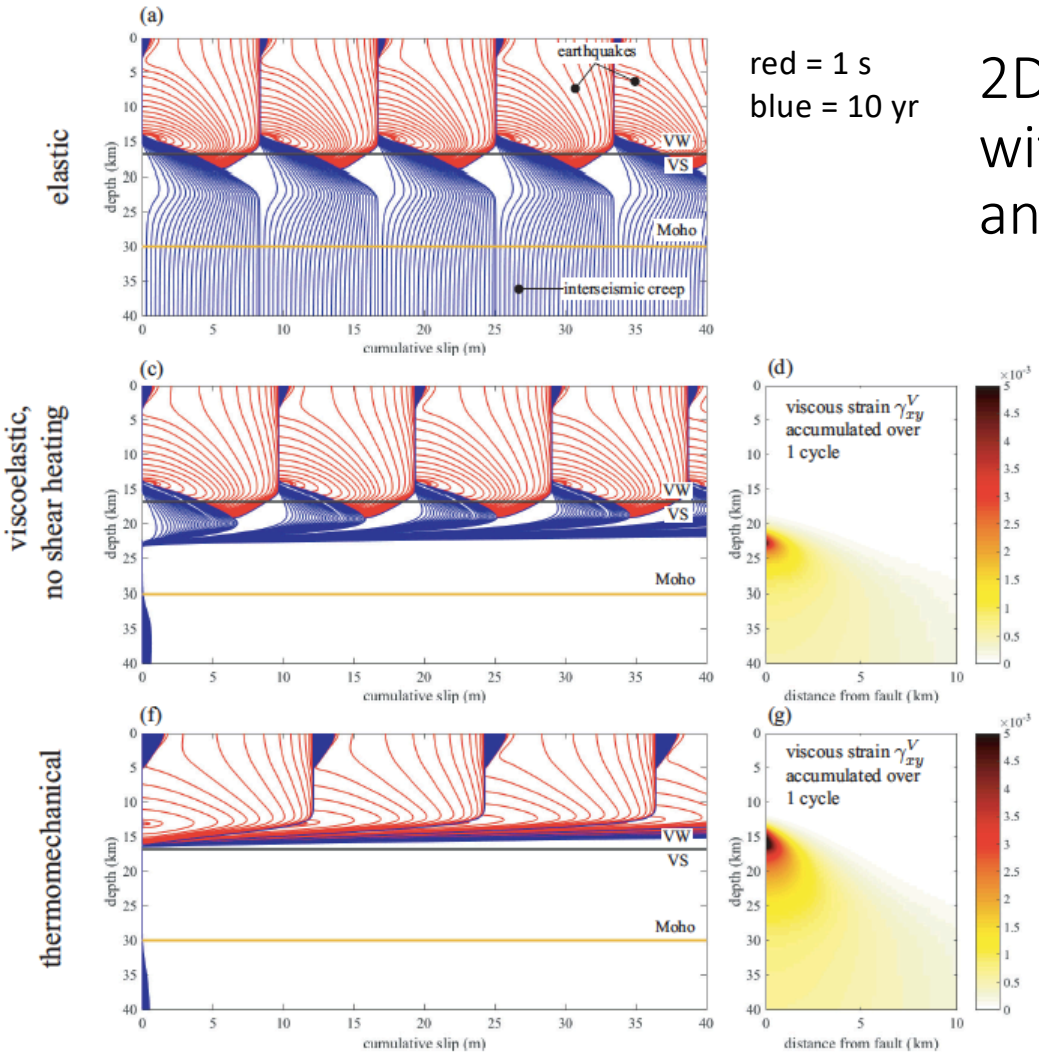
Temperature either fixed to 1D geotherm (above, "without shear heating" models) or allowed to evolve by solving energy equation ("thermomechanical" models)

- Rate-and-state friction fault with VW-VS transition at fixed depth (~16 km)
- Temperature-dependent power-law dislocation creep flow law everywhere, though low T near surface → effectively elastic upper crust
- ***Transition between localized fault slip and distributed viscous flow determined as part of solution, not specified a priori***

[Allison, PhD thesis 2018]

2D strike-slip cycle simulations with power-law viscoelasticity and thermomechanical coupling

red = 1 s
blue = 10 yr

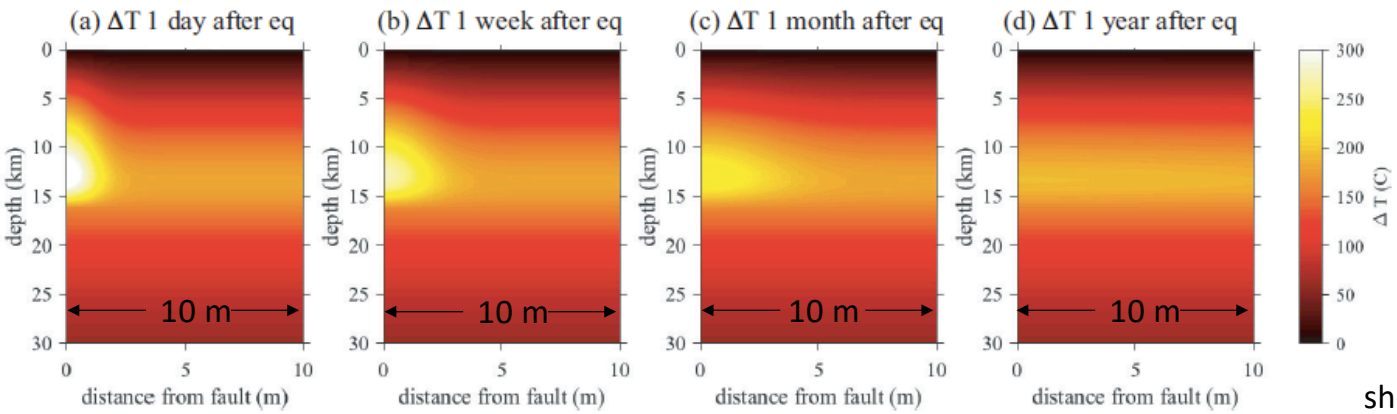


change in recurrence interval and slip/event indicates change in how seismogenic zone is loaded, though EQ nucleation depth and rupture depth is identical to elastic case

heating and weakening of lower crust effectively eliminates deep aseismic fault creep, raising BDT so that it limits rupture depth

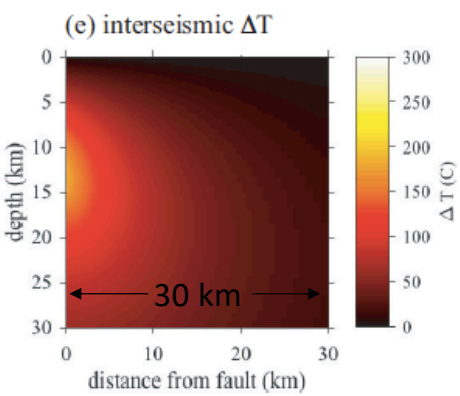
[Allison, PhD thesis 2018]

Shear heating creates thermal anomaly, which reduces effective viscosity and hence shear stress

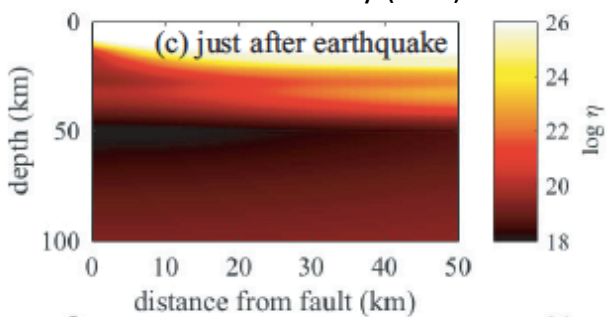


thermal anomaly (ΔT relative to 1D ambient geotherm) created by

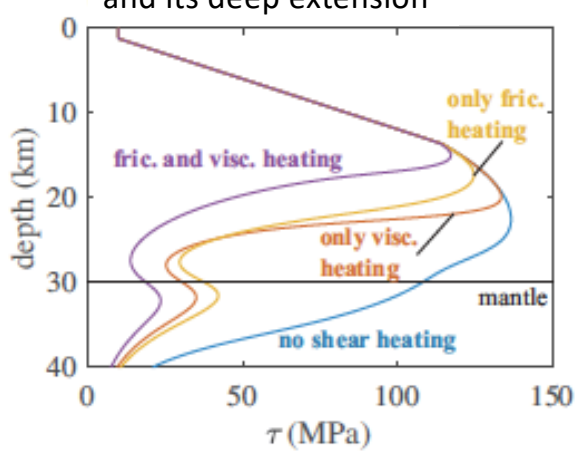
- frictional shear heating
- viscous shear heating



effective viscosity (Pa s)



shear stress on fault and its deep extension



[Allison, PhD thesis 2018]

Fundamental to both single-event and sequence simulations is effective normal stress, but current practice simply imposes fault pore pressure

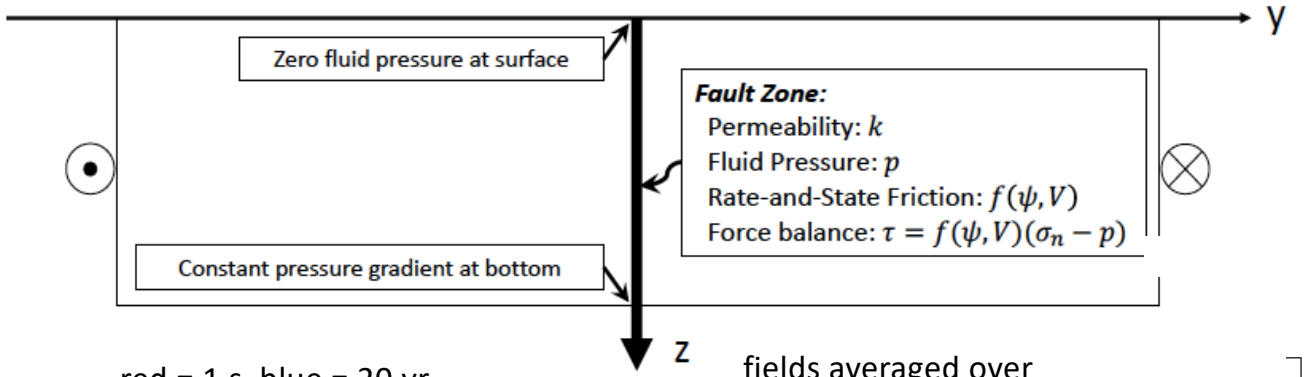
common choices for effective normal stress:

- lithostatic-hydrostatic (or similar linear increase with depth)
- independent of depth (possible if pore pressure tracks lithostatic gradient)

and it is often tuned, along with friction, as model parameter to produce desired stress drop, moment, ground motion amplitude, etc.

more work is needed!

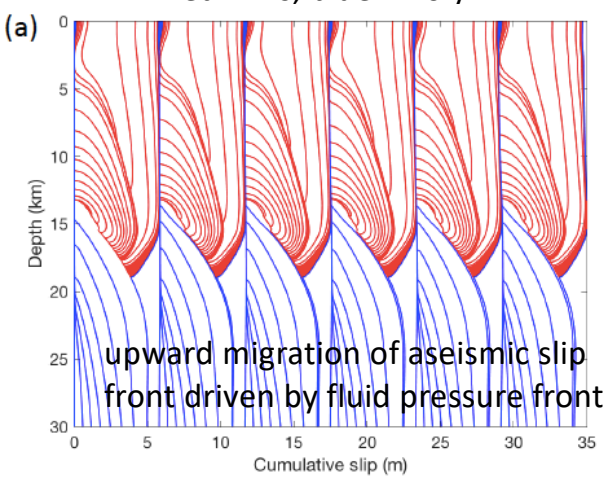
Cycle simulations accounting for fault-zone pore pressure evolution



New ingredients:

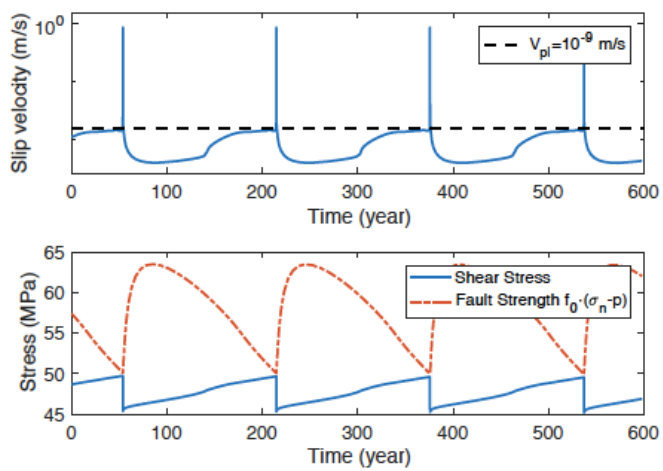
- **fluid transport** by Darcy flow along permeable fault zone
- **permeability evolution**: coseismic increase and interseismic healing

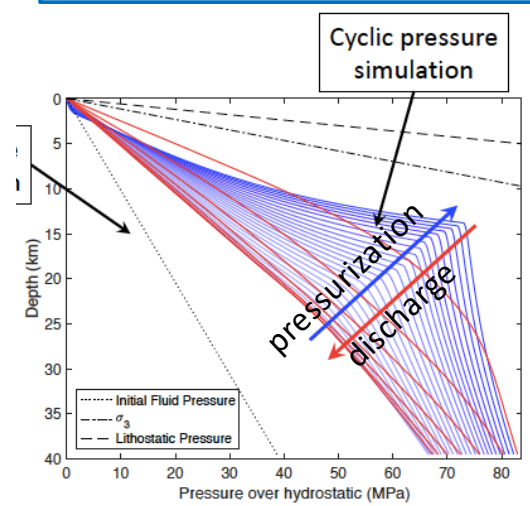
red = 1 s, blue = 20 yr



[Zhu, Allison, Dunham, SCEC, 2018]

fields averaged over seismogenic depth (20 km)





lines every 5 yr:

- red: overpressure is (partially) lost during discharge phase ~30 yr after earthquake
- blue: after healing reduces permeability, overpressure gradually builds

Topics for discussion

- **Fault shear zones, shear resistance, weakening mechanisms**
  - need to go beyond rate-and-state or slip-weakening to understand fault strength evolution
  - thermal pressurization and dynamic weakening, low stresses on major faults (open challenges: incorporate shear localization/delocalization dynamics over cycle and during rupture, how does dynamic weakening cease at depth?)
  - roughness: high-frequency radiation and ground motion simulation applications; shear resistance from roughness drag, importance of inelasticity to saturate resistance and stress levels, but how to reconcile with energy balance?
    also, evolution of stress heterogeneity over multiple cycles
  - weakening by effective stress reduction from bimaterial and poroelastic effects, even in aseismic sliding
  - validation by comparison with near-source strong motion records, heat flow constraints, induced seismicity and other indicators of stress and pore pressure state in crust, scaling of source properties (stress drop, fracture energy, radiated energy and radiation efficiency) with magnitude, geologic constraints on structures (damage zone width, localization features, fault zone thermo-poro-mechanical properties), lab experiments
- **Inelasticity: plasticity and viscoelasticity**
  - plastic strain is inevitable around complexities, limits extreme ground motion, and possibly controls fracture energy
  - viscoelasticity might control rupture depth, loading of seismogenic zone, post- and interseismic response
- **Fluids**
  - work on fluid transport and pore pressure evolution over cycle time scales is just beginning
  - permeability and porosity evolution (in brittle and ductile regimes), fluid generation by metamorphic reactions